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Coseismic and monsoon-triggered landslide impacts on remote trekking infrastructure, Langtang Valley, Nepal

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Short title: Landslide impacts in Langtang, Nepal

Abstract: In 2015, the M_w 7.9 Gorkha earthquake struck Nepal, triggering thousands of landslides across the central and eastern Himalayas. These landslides had many adverse effects, including causing widespread damage to low-grade transport routes (e.g. tracks, footpaths) in rural regions that depend on tourism for survival. Langtang Valley is a glacial/periglacial landscape located 60 km north of Kathmandu. It is one of the most popular trekking regions in Nepal and has been severely affected by Gorkha earthquake-triggered and monsoon-triggered landsliding. Here, qualitative and quantitative observations from fieldwork and remote sensing are used to describe the materials and geomorphology of the landslides across Langtang Valley, and to quantify the extent to which coseismic and monsoon-triggered landslides have impacted upon Langtang's trekking infrastructure.

The dominant bedrock materials involved within Langtang landslides are found to be a range of gneisses and intruded leucogranites. In total, 64 landslides are found to have intersected trekking paths across Langtang, with coseismic and monsoon-triggered landslides impacting ~ 3 km and 0.8 km of path respectively. It is observed that the practice of re-constructing paths through unstable landslide deposits is leaving the trekking infrastructure across Langtang increasingly vulnerable to future failure.

Earthquakes have long been recognised as a primary trigger of landslides (Keefer 1984), with the potential to initiate thousands of slope failures over relatively small regions (e.g. Harp & Jibson 1996; Xu *et al.* 2014). Such coseismic landslides can typically be distinguished from monsoon-triggered landslides by their tendency to occur at ridgelines or other major breaks in slope (Densmore & Hovius 2000). On 25th April, 2015, the M_w 7.9 Gorkha earthquake triggered over 24,000 slope failures across central-eastern Nepal (Roback *et al.* 2018). The characteristics and distributions of these landslides have been variably documented by previous, largely remote-sensing dominated, studies. For example, Roback *et al.* (2018) find that the distributions of these landslides are best predicted by the overlap of high Peak Ground Acceleration (PGA) and steep slopes, whilst Kargel *et al.* (2016) suggest that these landslides are most densely distributed where PGA was greater than 0.6 g. Similarly, statistical analysis by Martha *et al.* (2017) suggests that slope and geology are the dominant controls on landsliding, which they propose, in agreement with Collins & Jibson (2016), is owing to the fact that steeper slopes have more exposed bedrock with less vegetation cover. Martha *et al.* (2017) also show that 64% of coseismic landslides occurred on the northern, down-thrown block of the fault, supporting the observations of Kargel *et al.*, (2016).

The economic and social impacts of the Gorkha earthquake have also been reported. The Centre for Disaster Management and Risk Reduction (CEDIM, 2015) estimates that the earthquake caused damage to, or destruction of, 550,000 buildings, deaths of 9,000 people, and economic losses of ~\$10 bn. Furthermore, the landslides associated with this event caused at least 500 deaths and over 2% of

the total economic losses attributed to the earthquake. Following this event, landslide research in Nepal has been focused on conducting national and regional scale landslide susceptibility analysis (e.g. Shrestha & Kang 2017; Roback *et al.* 2018), as well as landslide analysis of the districts surrounding Kathmandu and the major road infrastructures linking Nepal and China (e.g. Xu *et al.* 2017; Acharya & Lee 2019). However, less research has been conducted into landslide hazard in and around Nepal's most popular trekking regions, despite the fact that rural tourism makes up over 5% of Nepal's economy (CEDIM, 2015). Between 1993 and 2014, Nepal received an annual average of 89,500 trekking tourists, but in 2015 received just 9,000, and in 2016 and 2017 still received some 20,000 less than the pre-earthquake average (Ghimire *et al.* 2018). Part of the problem is that Nepal's trekking infrastructure is remotely located and dominated by low-grade paths, which, as this feature will demonstrate, are severely impacted by coseismic and monsoon-triggered landsliding.

The aim of this feature is to use qualitative and quantitative observations to examine the interaction between landslides and trekking infrastructure in Langtang Valley, one of Nepal's most popular trekking regions, located 60 km north of Kathmandu, and 70 km east of the Gorkha earthquake epicentre (Fig. 1). In October 2018 field terrain evaluation was conducted to assess the composition and characteristics of coseismic and monsoon-triggered landslides across the valley. We firstly describe the geologic materials involved in the Langtang landslides, followed by geometric analysis to quantify the total length of Valley, and total length of trekking paths, that have been impacted by landslides. We then describe the morphologies and characteristics of some specific landslides that have contributed to this impact, before briefly considering the impact that landslides are having on the future vulnerability of trekking paths across Langtang Valley.

Methodology

Field data collection occurred along the main trekking routes in Langtang Valley between Syapruwesi and Kyanjin Gumpa, a total distance of approximately 50 km (Fig. 2). An inventory including both

coseismic and monsoon-triggered landslides was developed using a GARMIN 78 hand-held GPS unit and a TruPulse laser range finder. Monsoon-triggered and coseismic landslides were differentiated using their relative hillslope position and morphology. For example, monsoon-triggered failures are typically smaller than coseismic failures, occur on monthly rather than decadal timescales, and tend to initiate near the hillslope toe (Densmore & Hovius 2000). These field data were validated post-fieldwork through time series interrogation of RapidEye 5 m spatial resolution satellite imagery (PlanetTeam 2017), which was also used to validate whether landslides were coseismic or pre- / post-seismic in nature.

Geological mapping allowed an assessment of the materials involved in different slope failures. Lithological descriptions targeted landslide debris and backscar bedrock areas (where safe to access), documenting their mineralogy, texture, and discontinuity type and configuration. *In situ* shear strength testing was also conducted using a ‘simple means’ approach that involves estimating intact rock shear strength based on the response of a rock to applied pressure from rock hammer blows and/or hand crumbling (Hack and Huisman, 2002). For example, a sample that crumbles in hand would be assigned a strength of < 1.25 MPa, whilst a sample that only chipped after several heavy hammer blows would be assigned a strength of 100 – 250 MPa. This method should ideally be conducted on intact bedrock, however, since field access was often restricted to landslide debris, this was not always possible. As such, where measurements were taken on landslide debris, we ensured that target samples were un-weathered, and at least 40 x 40 cm in size. This method has been shown to give a more representative estimate of rock strength than more elaborate testing (Hack and Huisman, 2002), and is the method used in the British Standard for geotechnical investigations (BS EN ISO 14689:2008). Geological assessments also documented non-land slipped outcrops for strength comparison. Locations of lithological analysis are shown in Fig. 2. These locations informed the geological map compilation (Fig. 2), where the outcrop pattern is interpreted using topographic contours. Other mapping involved using GPS and remote sensing to delineate pre- and post-earthquake path locations.

Once the above data were collated, it was possible to quantify the total length of valley impacted by differently triggered landslides. This was estimated by fitting minimum bounding-area rectangles to all landslides in our inventory, except those mapped as dormant events with no known trigger, using the ArcGIS Minimum Bounding Geometry tool. This tool fits a minimum bounding rectangle that fully encloses each landslide polygon. As the runout direction, and thus resulting rectangle length, of each landslide is approximately perpendicular to the Valley strike, summing the rectangle widths gives an estimate of the total valley length impacted. Furthermore, by using the ArcGIS intersect tool to calculate the total length of intersection between our landslide polygons and a shapefile of the main paths across the valley, it was possible to estimate the total length of paths impacted by both coseismic and monsoon-triggered landslides.

Geological observations

Langtang Valley sits within the Greater Himalayan Sequence, structurally bounded by the Main Central Thrust (MCT) to the south and the South Tibetan Detachment (STD) to the north. Regional scale (1: 250,000) geological maps held by the Nepal Department of Mines and Geology indicate that the bedrock geology of the central-eastern Himalayas is dominated by gneisses, migmatites, quartzites schists, and pervasive Miocene leucogranite intrusions. However, these maps lack detailed lithological information on Langtang Valley, with simple generalization as ‘Undifferentiated gneisses’. Thus, our fieldwork allowed a more detailed, qualitative and quantitative assessment of the materials involved in the Langtang landslides, previously lacking in published materials.

Four lithological units were identified within landslides across the valley. The first unit, termed here as the Syraprubesi Formation, is a gneiss dominated by muscovite, biotite and quartz, with subordinate components of plagioclase and garnet (e.g. Fig. 3a). This unit is medium- to coarse-grained, with average grain size of 0.3 – 3 cm. The minerals were generally platy, with elongated

plagioclase orientated parallel to foliation and a strong mylonitic fabric. *In-situ* strength tests indicate that this unit is hard (50 – 100 MPa). The second unit, the Bamboo Formation, is a gneiss dominated by muscovite, biotite and quartz, with subordinate components of tourmaline (e.g. Fig. 3b). This unit was very similar to unit one, but with a larger average grain size of 1 – 3 cm, and with the addition of tourmaline. Unit two had a much higher proportion (60 – 70 %) of quartz and biotite compared to unit one, but maintained the mylonitic fabric. Strength tests suggest that unit two is very hard (100 – 250 MPa). Unit three, named the Langtang Formation, is a coarse-grained (2 – 6 cm) leucogranite, dominated by muscovite, tourmaline, epidote, and occasionally garnet (e.g. fig. 4a). Unit three was commonly found intruded into units two and four, and has a strength of 50 – 250 MPa. This unit was often observed in the source zones of earthquake triggered rockfalls (e.g. fig. 4b). We hypothesize that the discontinuities induced by the intruded leucogranite dykes and sills have reduced the shear strength of the bedrock, making failures in regions with this unit more likely. Unit four, termed here the Lower Tsergo Ri Formation, is a biotite, plagioclase, muscovite, quartz, semi-pelite schist (e.g. fig 4c). This unit was finer grained than the other units (average grainsize 0.25 – 1 cm) and had an estimated strength of 100 – 250 MPa. This unit was dark to light grey in colour and was frequently observed to be in contact with leucogranite.

Landslide observations

In total, our field-based landslide inventory contains 154 coseismic landslides, which were classified using the BGS definitions and typologies (British Geological Survey, 2019) as being 58% falls, 27% slides and 15% flows. A further 29 monsoon-triggered and inactive/dormant landslides that occurred pre- or post-earthquake were also mapped (Fig. 2). In terms of total area, 46% of the mapped landslides were $< 1.0 \times 10^4 \text{ m}^2$, 48% were $1.0 \times 10^4 - 1.0 \times 10^5 \text{ m}^2$, and 6% were greater than $1.0 \times 10^5 \text{ m}^2$, with the largest event being the Langtang Avalanche, which had a total mapped area of approximately $1.86 \times 10^6 \text{ m}^2$. Our landslide inventory is one of several that covers the region. For example, the remotely-sensed Gorkha earthquake-triggered landslide inventories of Kargel *et al.*

(2016), Lacroix (2016), Martha *et al.* (2017) and Roback *et al.* (2018) all cover Langtang Valley, and identify comparable numbers of landslides across the main trunk of the valley. Minor differences between these inventories and ours are likely caused by the varying spatial resolution of satellite sources used, and the fact that we only mapped landslides visible from the main trekking routes and so did not include those triggered along tributary valleys. A further difference is that our inventory is field-based, and thus represents the locations and extents of landsliding three years since the earthquake occurred, unlike the previous inventories which represent the immediate post-earthquake landslide distribution.

An aim of this paper was to quantify the impact of landslides in terms of length of valley affected and length of paths affected using the GIS methodology outlined in the methods section. Coseismic landslides are found to have impacted 14 km of the valley, whilst monsoon-triggered landslides impacted just 1.5 km. In total, 64 of the 183 landslides in our inventory were found to have intersected trekking paths, with coseismic landslides impacting ~ 3 km of path, and monsoon-triggered landslides impacting ~ 0.8 km of path. The following sections describe the geomorphology and characteristics of key examples of the landslides that contributed to this impact.

The Langtang Avalanche

The Langtang Avalanche is perhaps the most renowned coseismic landslide to have occurred during the Gorkha earthquake, having entirely destroyed the village of Langtang with the loss of at least 300 lives. This event was a complex compound occurrence that began when earthquake strong ground motion caused a portion of glacial material within an ice-carved hanging valley, as well as a portion of bedrock approximately 500 x 1000 m in size (Fig. 5a), to collapse (Nagai *et al.* 2017). The deposits from this event have been previously estimated through remote sensing techniques to have a depth of ~60 m, an area of 0.63 – 0.88 km², and a volume of 5.51 – 9.66 x10⁶ m³ (Lacroix 2016; Nagai *et al.* 2017). Pertinent to this study is the interaction between the landslide deposits and trekking paths. This

event completely buried a ~ 500 m long section of the main trekking path, which has since been reinstated over the landslide deposits. The material within the deposits is mostly gneisses (unit 2) and leucogranites (unit 3). Fig. 5b shows the position of the new trekking path at the point where a river has incised through the deposits. The path here is highly precarious, with some sections < 30 cm wide beneath a > 80 °, 10 m high slope of loose deposits, which are vulnerable to movement during a future trigger event. Furthermore, the path crosses over a narrow tunnel that has been created by the river (Fig. 5c). This portion of the deposits is unstable, and several boulders were witnessed falling from beneath the tunnel into the river. This demonstrates that the Langtang Avalanche is continuing to impact the safety and vulnerability of Langtang's trekking paths more than three years since the initial failure occurred.

Debris slides

Whilst the Langtang Avalanche has undoubtedly had the greatest single impact on trekking infrastructure, the cumulative impacts of smaller, but more widespread, coseismic failures cannot be understated. For example, coseismic debris slides were pervasive along the lower, western portion of the valley. Fig. 6 shows a debris slide that initiated near the ridgeline of a > 55° hillslope covered by grassland in the lower slopes and trees and larger shrubs in the upper slopes. The bedrock geology of the scar of this failure is dominated by the gneisses of unit 1. However, as the failure is shallow (< 0.5 m), and has mostly disturbed the unconsolidated regolith material overlying the bedrock, it is defined as a debris slide rather than a rockslide. In terms of impact on trekking infrastructure, the localised runout of this failure resulted in only a small volume of material intersecting the path. However, more concerningly, it was observed that this debris slide came close to damaging several electricity pylons. These pylons connect to the new hydropower station near Kyanjin Gompa, and are a vital component of Langtang's energy infrastructure.

Unconstrained rockfalls

Unconstrained rockfalls were frequently observed to bury the main trekking route. Fig. 7a shows an example of such an event. The material in the deposits confirm that this failure occurred within the bedrock itself, which was composed of the unit 1 gneisses. The material from this failure buried a 30 m long segment of the trekking path, reportedly killing 30 people. This landslide demonstrates that even relatively small-scale events have the potential to cause loss of life when hazard overlaps with vulnerability. Since the initial failure, a new trekking path has been re-dug through the deposits, with no attempt at any mitigation against potential monsoonal reactivation of debris material. As such, this section of the path should be considered at high-risk of being damaged or blocked by reactivated landslide material in the future. Fig. 7b shows a debris fan from a combined rock/debris fall and a rock/debris flow. The source zones for the flow and the fall appear to be at major $> 55^\circ$ and $> 65^\circ$ breaks in slope. The path of the flow appears to have been controlled by the existing hillslope morphology, with a knoll splitting the flow into two channels just before the main rockfall debris fan. The flow travelled for ~200 m before joining the main debris fan, whilst the debris from the main rockfall travelled ~100 m. This failure totally buried a ~40 m section of the trekking path, and is reported to have killed 20 people. Similar to the previous examples, the position of the new trekking path now lies on top of the landslide deposits, with no measures aimed at moderating future instability. As such, this section of the path is again considered to be at high risk of being blocked, or otherwise impacted, by future reactivation of landslide debris.

Monsoon-triggered landsliding

As well as coseismic landslides, monsoon-triggered landslides were frequently observed across the valley, and care must be taken when distinguishing between these different triggering mechanisms. Fig. 8 shows a typical monsoon-triggered translational debris slide that has occurred on a forested, $> 45^\circ$ hillslope. This slide has a height of ~30 m, and completely destroyed an ~45 m wide section of

the path below, which has since been re-built. The sides of the new path have been supported with small, < 0.5 m high walls of unconsolidated debris material. The debris material remaining above the new path is highly unstable, with several (> 10 m wide) blocks balancing within the deposits. This material will be highly susceptible to movement during subsequent monsoon-seasons, and as such remains at-risk of impacting the trekking path further.

Conclusions

Geometric analyses of our field data show that coseismic and monsoon-triggered landslides have intersected over 3.8 km of trekking path, resulting in significant loss of life and damage. Furthermore, our observations of the morphology and characteristics of these landslides demonstrate that the response to this damage has been to simply re-dig new, unstable paths through the landslide deposits, with no attempt at mitigation against future movement. This is a labour intensive, but low-cost practice which has the advantage of allowing the trekking paths to be re-opened quickly after a landslide. However, such an approach has had the major disadvantage of leaving the trekking paths highly susceptible to blockage or damage by future monsoon- or seismic-triggered reactivations of material, resulting in an increased risk of subsequent fatalities or damage across Langtang.

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Figure Captions

Fig. 1. Overview location map of Nepal and the Langtang Valley watershed.

Fig. 2. Map of the lower portion of Langtang Valley that was the focus of the fieldwork. The main geological unit observations and estimated extents, towns, trekking routes and mapped landslides are displayed. The locations of the landslides in figures 4-8 are also highlighted.

Fig. 3. (a) Example material of unit 1, a muscovite, biotite, plagioclase, quartz, garnet gneiss, termed here as the Syraprubesi Formation. Note the strong mylonitic fabric. **(b)** Example material of unit 2, a muscovite, biotite, plagioclase, quartz, tourmaline gneiss, termed here as the Bamboo Formation. Again, note the strong mylonitic fabric, and the dominance of quartz and biotite.

Fig. 4. (a) Example material of unit 3, a leucogranite with large, 1 – 5 cm, crystals of tourmaline, termed here as the Langtang formation. **(b)** A typical rockfall found in the eastern, higher elevation portions of Langtang Valley, with large intrusions of leucogranite within the bedrock of the scar. **(c)** Example material of unit 4, a finer grained, 0.25 – 1 cm, biotite, plagioclase, muscovite, quartz, semi-pelite schist, termed here as the Lower Tsergo Ri Formation.

Fig. 5. (a) Front view of the Langtang Avalanche. Note the clear striations on the relatively smooth back-scar and change in slope of the back-scar which is indicative of a rotational element of movement. **(b)** A section of the Langtang Avalanche deposits that have been incised by a river. The precarious location of the new trekking route is shown by the red-dashed line. **(c)** A tunnel incised underneath the landslide deposits by a river. Red line indicates the current position of the trekking path over the top of the tunnel.

Fig. 6. Debris slide located ~4 km east of Syraprubesi. Red-dashed line indicates the main trekking path that has been impacted by the failure. The yellow boxes indicate the position of electricity / telegraph poles.

Fig. 7. (a) Debris fan of an unconstrained rockfall located ~ 4 km west of Thangsyap, which has intersected the trekking path (red-dashed line) below. **(b)** Debris fan of material from a debris flow and rock/debris fall that also intersected the trekking path (from where this photo was taken).

Fig. 8. Monsoon-triggered translational slide located 2 km east of Syraprubesi. A new trekking path (red-dashed line) has been constructed through the deposits, yet many large unstable boulders remain above the path.















